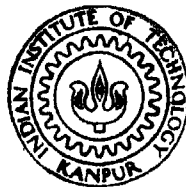


RESIDUAL STRESSES DURING CONVENTIONAL AND PLASMA HOT MACHINING OF En-24 STEEL

By

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APRIL 1985

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In Partial Fulfilment of the Requirements
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By
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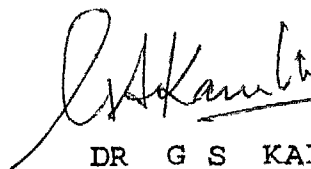
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been carried out under my supervision and has not
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April, 1985



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SYNOPSIS

This report presents investigation into residual stress in Conventional Machining (CM) and Plasma Hot Machining (PHM) on En-24 steel. A comparison of PHM with CM is made

Test specimens are made from En-24 steel by CM and PHM at feed rates ranging from 0.05 to 0.25 mm/rev and cutting speeds ranging from 36 to 50 m/min. Fresh cutting edge is used for final cut of each specimen. PHM is done with 2.75 KVA micro plasma welding unit, Argon gas pressure and flow rate of 6 kg/cm² and 3 lit/min respectively.

A technique is used to continuously etch a cylindrical specimen and simultaneously record the dimensional change. A solution of 20% nitric acid in ethanal is used as etchant. Residual stress at any depth is calculated using Baur and Heyn equation from rate of change of elongation, instant elongation and etching rate

The behaviour of residual stress with cutting speeds and feed rates during CM and PHM is presented

Following conclusions are drawn -

- (1) Residual stress is compressive during CM
- (2) Residual stress is tensile near the surface during PHM
- (3) Depth of residual stressed layer is nearly same at all feed rates for a constant speed and depth of cut.
- (4) Minimum depth of residual stressed layer occurs at 0.15 mm/rev feed in CM and PHM.

CHAPTER-1

INTRODUCTION AND LITERATURE SURVEY

1.1 INTRODUCTION

High strength temperature resistant and refractory materials are being used in various industries. Machining of such type of materials creates a number of problems e.g. less metal removal rate, short tool life etc. in Conventional Machining processes. Techniques of Hot Machining provide a means of solving some of these problems. Hot Machining consists in the application of localized heating to reduce the shear strength of the work-material in the vicinity of the cutting zone. Due to reduction in shear strength of the work-material at higher temperature, cutting forces and tool wear are reduced.

The main requirements for a suitable heating method are

- (a) Heating should be intense and confined to the shear zone.
- (b) The time lapse between heat application and cutting should be small so that minimum heat

is transferred into the workpiece to avoid metallurgical damage.

- (c) It should be economical both in installation and operation.

Various heating methods [1,2] suggested for Hot Machining are flame heating, furnace heating, resistance heating, induction heating, radio frequency heating and plasma arc heating. The relative advantages and disadvantages of these methods have been discussed by Pentland, Wennberg and Mehl [2]

Plasma arc heating is used in the present investigation due to its high specific heat input and ease of controlling the heat input into the workpiece

1 2 LITERATURE SURVEY

Hot Machining has been under investigation for the last forty years as a method for improving machinability of materials which are otherwise difficult to machine.

1.2.1 Plasma Arc Heating

Plasma is produced when gases are ionised by passing through an electric arc. The process of ionisation is accompanied by absorption of heat and the process is carried out in a torch having a tungsten cathode

and a brass nozzle which acts as anode. A shielding gas is generally used which envelops the plasma gas and reduces the loss of heat to the environment. Water supply through the torch keeps the temperature of the nozzle at a low level and prevents damage to the nozzle.

Plasma arc can be used in two modes viz (i) transferred arc mode and (ii) non-transferred arc mode. In transferred arc mode, the nozzle and workpiece are made anode. Pilot arc is struck between the cathode and the nozzle. As soon as the main arc is established, workpiece acts as anode, thereby, avoiding heating of the nozzle.

In non-transferred arc mode, the nozzle alone acts as the anode. Pilot and main arc are established between cathode and the nozzle and the arc is electrically neutral. However, the nozzle is subjected to impinging electrons causing greater damage of the nozzle.

Transferred arc mode can be used for electrically conducting materials only. Further, it is difficult to connect rotating workpiece to the anode of supply in turning operation. Hence, non-transferred arc mode is used in the present investigation.

1 2.2 Advantages of Plasma Arc Heating

- (i) Heat is confined to the material which is just about to be removed
- (ii) Good control of temperature can be obtained
- (iii) Depth of heat into the workpiece can be controlled
- (iv) The method can be used for electrically conducting as well as non-conducting materials
- (v) High heat transfer efficiency of the order of 55% is achieved [Hinds and Almeida [6]]

Pattee, Meister and Monroe [3] have investigated plasma arc characteristics. The operating voltage of plasma arc is largely influenced by the gas used, the flow rate of plasma gas and nozzle orifice diameter.

Metcalf and Quigley [4] studied the energy transfer in plasma arc welding. The heat transfer is due to radiation (30%), convection (45%) and anode effects (25%) at the workpiece surface.

Hinds and Almeida [5,6] opined that plasma arc heating is the most efficient heating method in turning operation. They observed that the heat transfer efficiency to the workpiece reduces slightly (5 to 10%) with increase in cutting speed and stand-off distance. They found that heat transfer is more effective in the range

of cutting speeds from 100 to 150 m/min for a gas flow rate of 4.0 lit /min, voltage of 44 volts, current of 100 amps and a stand-off distance of 9 mm while turning En-31 steel.

Reznikov et al [7] carried out research on temperature occurring during turning operation with plasma pre-heating. The effect of heating by the ancillary source alone is considered and the heat resulting from cutting is not included. They found that plasma pre-heating of the workpiece in the vicinity of the shear surface causes pre-heating to a fairly high temperature resulting in the reduction of work-material strength.

1 2 3 Residual Stresses

Residual stresses are generated following inhomogeneous plastic flow caused by external forces or thermal gradients, gliding, twinning, kinking, grain boundary effects, orientation effects, dislocation etc.

Turning, grinding and other machining operations introduce residual stresses in machined parts. Stresses may be of significant magnitude upto depth of 0.35 mm below the surface of machined component [Liu and Barash [8]].

Residual stresses cause dimensional instability. If the residual stresses are relieved or otherwise changed

during the life of a component, dimensional change occurs. Residual stresses accelerate the occurrence and diffusion of cracks. The selection of an acceptable machining operation requires knowledge of the residual stresses produced by such operations on certain critical parts

1 2 4 Measurement of Residual Stresses

The residual stresses are measured by the following methods -

- (i) Radius of Curvature method
- (ii) Holographic and Speckle Interference method
- (iii) X-ray method.
- (iv) Continuous Etching method

Liu and Barash [8] measured the residual stresses of thin, flat specimen by the Radius of Curvature method. This method utilizes the fact that removal of stressed layer from one side of a specimen will cause the specimen to bow. The stressed layer were removed by using acid solution (80% distilled water, 14% hydrofluoric acid, and 6% nitric acid)

Rassokha [9] presented two methods of (1) Holographic and (2) Speckle Interference examination for residual stress measurement in welded joints produced by argon-arc and laser welding.

In Holographic method, the specimen was attached to the stage of a SIN apparatus, and a PE-2 special photographic plate is used to record a hologram of the initial state (Fig. 1) A small volume of material is removed by drilling without disturbing the specimen and a hologram of new surface state is recorded on the same plate

The residual stresses were considered to be directly proportional to the displacement observed at any one point on the edge if the material deforms in the linear elastic range for the corresponding residual stresses.

In Speckle Interferometry method , when a narrow laser beam is passed through the specimen, parallel interference fringes are formed on the screen The distance between fringes is related to the displacement of a point through which the laser beam passes in the Speckle Hologram. If one scans the hologram, one gets the magnitudes and directions of the displacement at a series of points near the edge of the hole. As removal of small volume of material (e g by drilling a small hole) is equivalent to applying a system of loads to the new surface so that the residual stresses at the surface are removed. They assumed that at the free surface and at the edge of the hole, tangential and normal

stresses are zero They reported that Speckle Interferometry is less sensitive but simpler than Holographic method

Doi and Ukai [10] proposed a theory of residual stress measurement by X-ray method under the consideration of its penetration depth with successive thin layer removal. Layers were removed by electrolysis with an electrolyte of H_2PO_4 and H_2SO_4 The stress evaluation was done by $\sin^2\Psi$ method They found that residual stress distribution by X-ray method is affected by absorption coefficient, stress gradient and removed thickness. They derived expressions considering these effects under consideration of X-ray penetration

Israeli and Papiar [11] used the Baur and Heyn equation for the purpose of measuring residual stress. Baur and Heyn introduced the spring model to determine the profile of longitudinal residual stress in a cylinder as described by Baldwin [12] They assumed that longitudinal residual stress is symmetrical around the axis of the cylinder. Each concentric layer is considered analogous to a spring, either stretched or compressed By removing a layer from the periphery, the force due to residual stress in that layer is relaxed. This relaxation causes length change in the cylinder The residual

stress in any removed layer is given by

$$S = E [A (de/dA) - e] \quad (1)$$

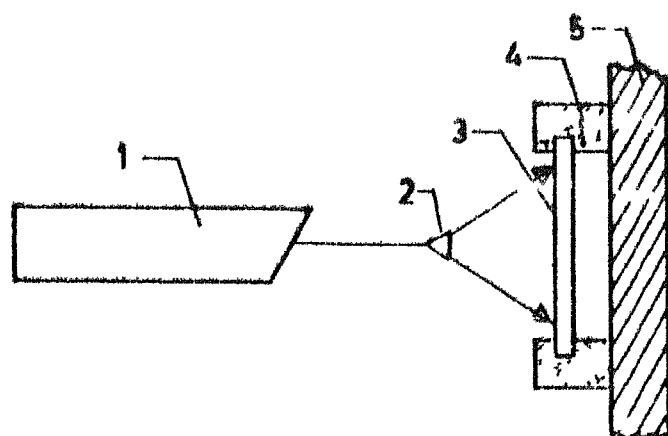
where, S is residual stress in the removed layer, e is instant strain, E is Young's modulus and A is cross-sectional area of cylinder

They developed a new technique to continuously etch a cylindrical specimen and simultaneously record the dimensional change continuously.

Eqn. (1) has been reduced in the form given below (eqn. 2) for a cylindrical specimen of original radius R_0 and original length L_0 . l is the instant elongation, h is the depth of the removed layer measured from original surface at time t and K is metal removal rate

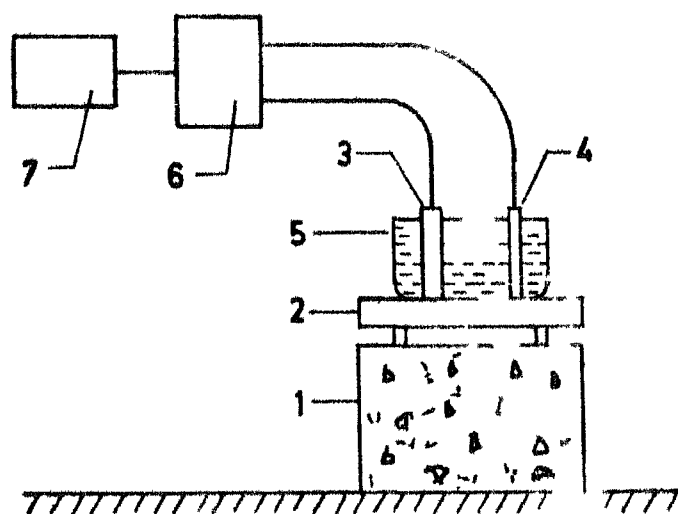
$$S = - \frac{E}{L_0} \left[\frac{R_0 - h}{2K} \frac{dl}{dt} + 1 \right] \quad (2)$$

Therefore, the residual stress at any depth h can be determined from a record of change in length with time provided K is known. They used ^{a solution} of 20% nitric acid and 80% ethanol for etching the steel specimen. The elongation of the specimen was measured with a linear variable differential transformer (LVDT). Two measuring heads were used, one placed on the specimen and the other on the reference rod (Fig. 2)



- 1 Laser
- 2 Microscope Objective
- 3 Photographic Plate
- 4 Plate Holder
- 5 Specimen

FIG 1 SCHEME FOR GENERATING DOUBLE-EXPOSURE HOLOGRAM (After Rassokha [9])



- 1 Stable Pier
- 2 Granite Plate
- 3 Specim Rod & LVDT Probe
- 4 Reference & LVDT Probe
- 5 Etching System
- 6 LVDT Power Supply
- 7 Recorder

FIG 2 SCHEME OF RESIDUAL STRESS DETERMINATION LAY-OUT (After Israeli and Papiar [11])

1.2.5 Effect of Machining on Residual Stresses

Leskovar and Peklenik [13] carried out turning tests on steel C4782 (JUS) and 42CrMoS4 (yield strength $\approx 610 \text{ N/mm}^2$) at cutting speeds from 20 to 200 m/min and feed rates from 0.04 to 0.314 mm/rev at a depth of cut of 1 mm using carbide P-25 tools.

Residual stresses were of great intensity in the layers directly underneath the surface, particularly at higher cutting speeds (Fig. 3)

Ovseenko et al. [14] investigated the effect of pre-heating before turning the workpiece on the residual stress. They carried out tests on cast iron LChKh28N2 with VK6M tools at cutting speeds of 15 and 60 m/min, feed rates of 0.05 and 0.5 mm/rev at a depth of cut of 1 mm. The blanks were pre-heated by ring type high frequency inductor.

The residual stresses were determined by the DAVIDENNOV method. The tangential residual stress was measured on rings ($d_{\text{out}} = 50 \text{ mm}$ and $d_{\text{in}} = 44.5 \text{ mm}$) by automatic recording of strain curve of a sample during continuous electrolytic etching of the stressed layers.

They found that pre-heating changes the amount and nature of residual stress distribution at higher speed. (Fig. 4) They ^{also} found that cutting speed has a

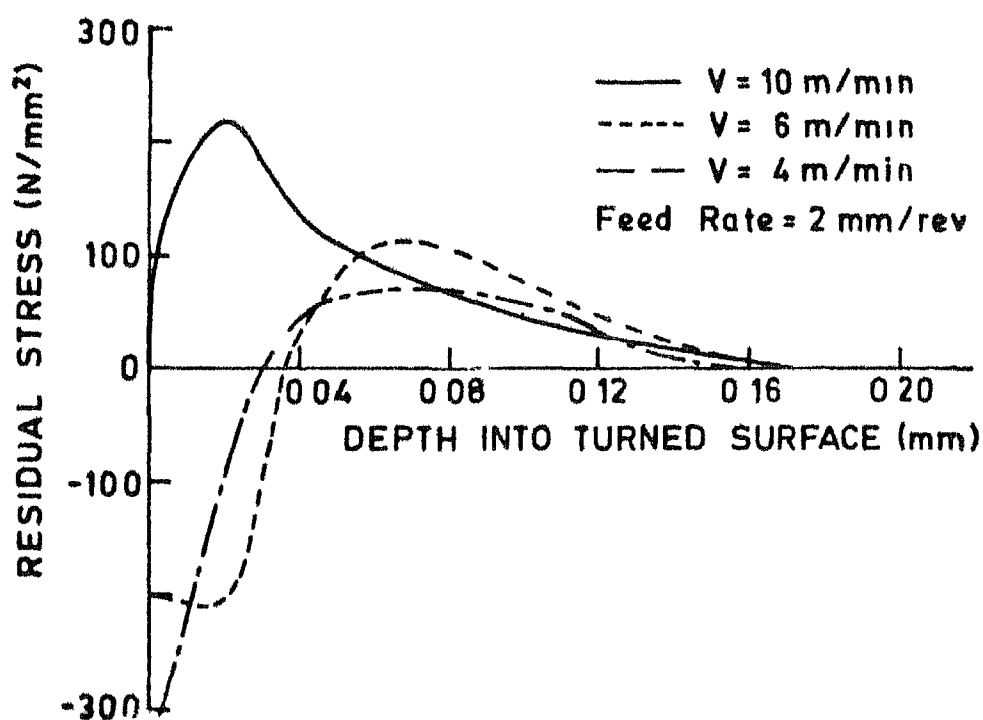
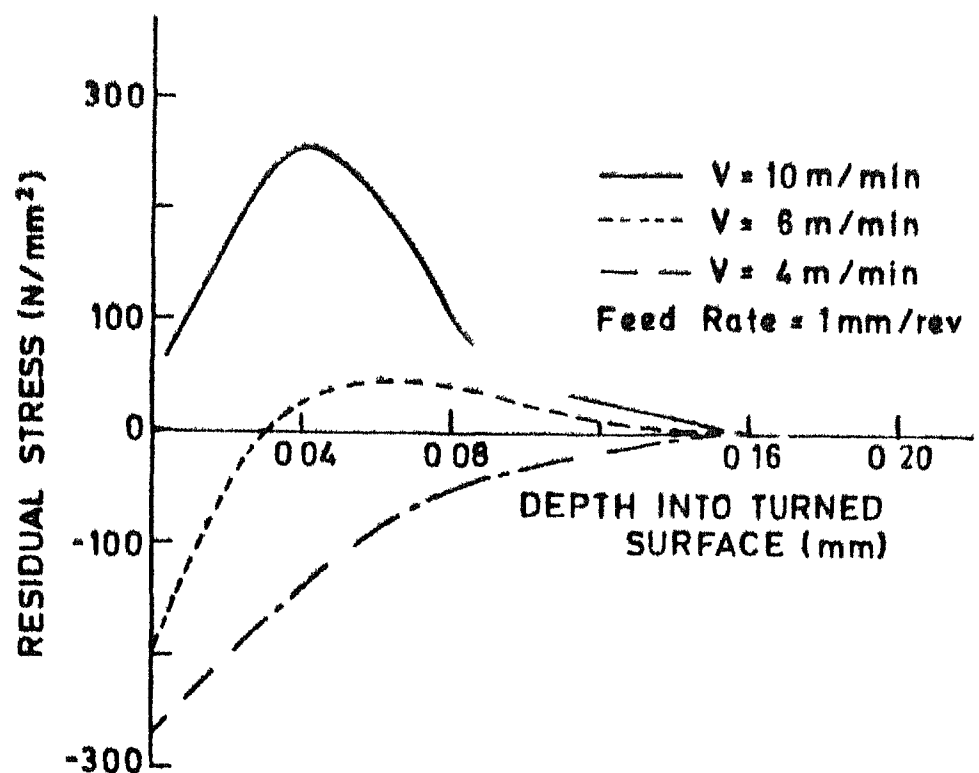


FIG 3 RESIDUAL STRESSES OF TURNED SPECIMEN
(After Leskovar and Peklenik [13])

considerable effect on the level and nature of the stress distribution. There is practically no difference in the value of residual stresses when machining with and without pre-heating at lower speed. (Fig. 4)

Liu and Barash [8] found residual stress (Fig. 5) by conducting tests at cutting speeds of 1.53 m/sec and 4.63 m/sec at depth of cut of 0.127 mm and 0.254 mm. They concluded that residual stresses of higher value are induced by decreasing the cutting speed at the smaller depth of cut. The smaller the depth of cut, the greater is the effect of cutting speed. At low speed, a smaller depth of cut produces higher tensile stresses. At higher speed, the reverse occurs (Fig. 5)

Doi and Ukai [10] measured residual stress distributions (Fig. 6) in an inner cylinder of needle bearing ($d_{out} = 38$ mm, $d_{in} = 32$ mm and length = 45.2 mm) of high carbon steel (JIS SUJ-2), oil quenched at 830°C and tempered at 150°C.

Israeli and Papiar [11] conducted turning tests on AISI-4340 steel and maraging steel-300 (solution heat treated) at cutting speed of 50 m/min, depth of cut of 0.3 mm and at feed rates of 0.015 to 0.20 mm/rev.

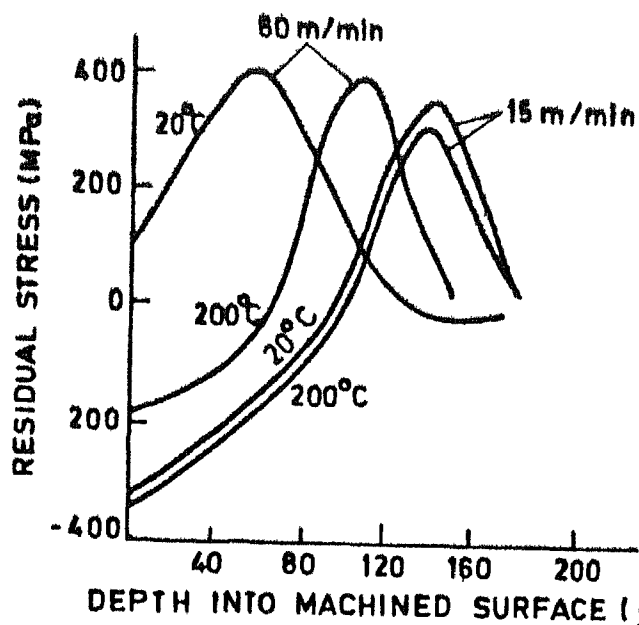


FIG 4 EFFECT OF PRE-HEAT TEMPERATURE ON RESIDUAL STRESS (After Ovseenko et al [14])

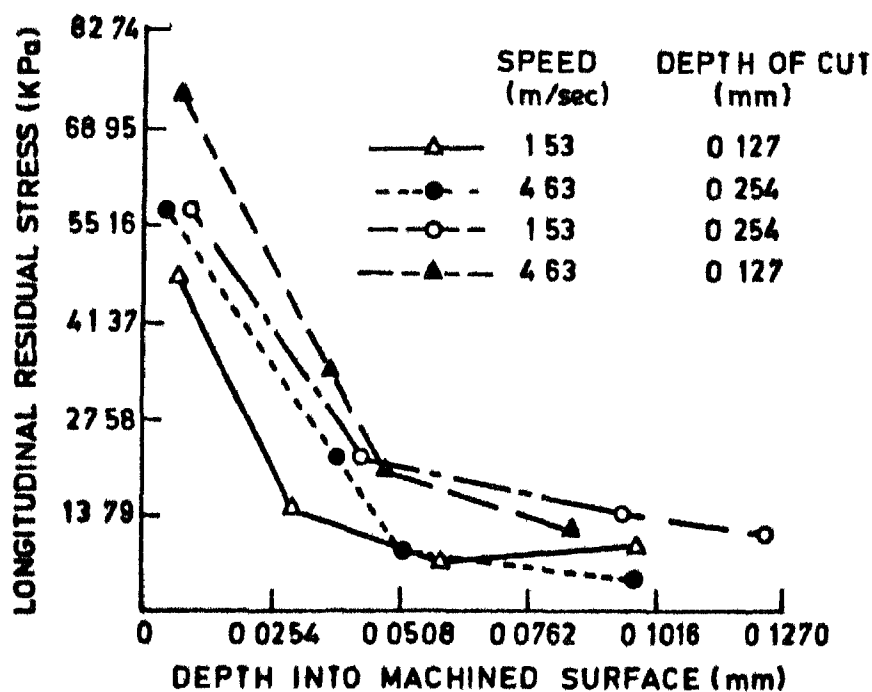


FIG 5 EFFECT OF CUTTING SPEED AND DEPTH OF CUT ON RESIDUAL STRESS (After Liu and Barash [8])

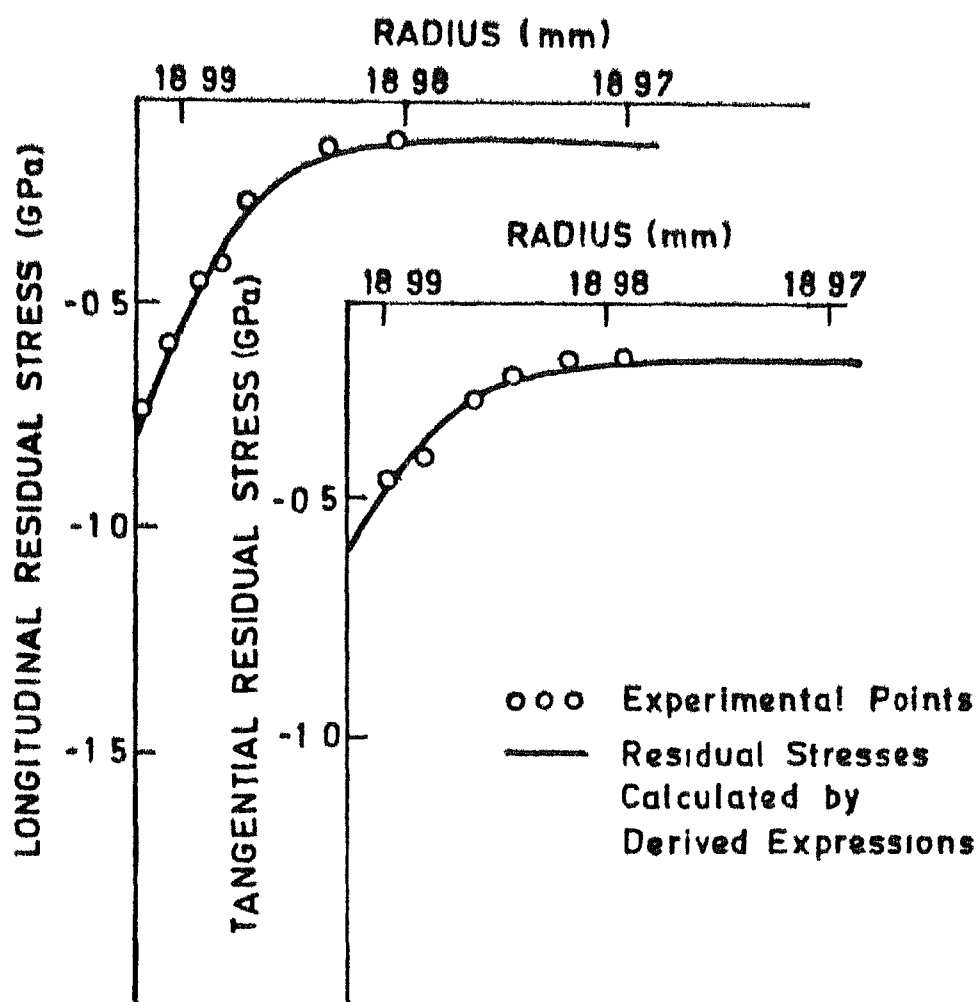


FIG 6 RESIDUAL STRESS DISTRIBUTION IN SUB-SURFACE (After Doi and Ukal [10])

Figures 7 and 8 show the residual stress profiles obtained for AISI-4340 steel and maraging steel-300 (solution heat treated) respectively. They inferred that there is a tendency for decreasing surface stress with increasing feed. They found that an increase of feed increases the depth of the residual stressed layer.

1.3 AIM OF THE PRESENT WORK

To study the residual stress, Conventional and Plasma Hot Machining tests are carried out on En-24 steel. Non-transferred arc mode of plasma arc heating is used.

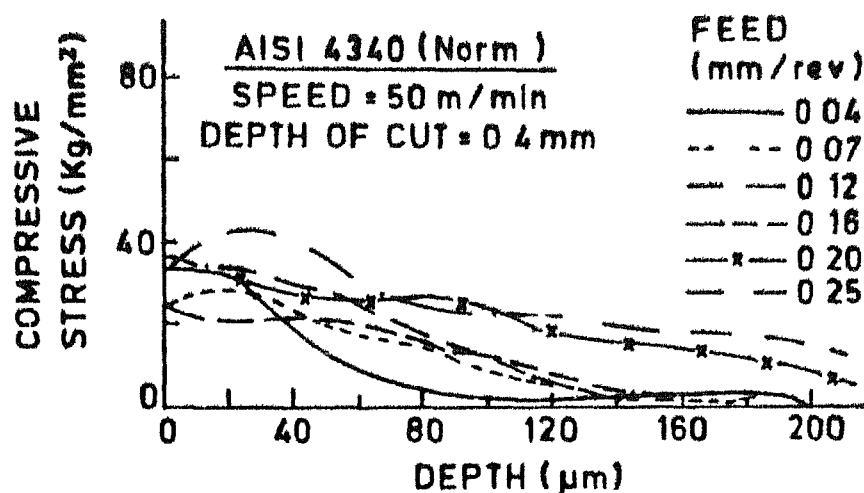


FIG. 7 RESIDUAL STRESS PROFILE OF TURNED 4340 STEEL
 (After Israeli and Papiar [11])

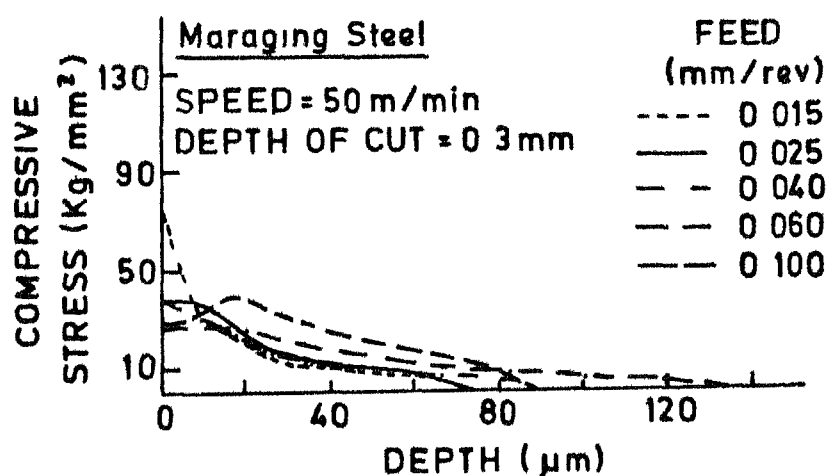


FIG 8 RESIDUAL STRESS PROFILE OF TURNED
 MARAGING STEEL (After Israeli and Papiar [11])

CHAPTER-2

EXPERIMENTAL SET-UP AND PROCEDURE

2 1 GENERAL

In present investigation, Conventional Machining (CM) and Plasma Hot Machining (PHM) are carried out on En-24 steel to study residual stress in feed direction in turned specimens. A comparative study between CM and PHM is made

2 2 EXPERIMENTAL SET-UP FOR PHM

The schematic diagram for PHM is shown in (Fig. 9) Micro plasma welding unit (2 75 KVA) is used as a heat source. Torch is held in a holder designed and fabricated by Chattopadhyaya [16] The configuration of the torch and the workpiece is shown in (Fig 10)

2.2 1 Experimental Conditions

Test specimens (Fig. 11) are made by turning En-24 steel (yield strength = 126 kg/mm^2 , ultimate strength = 190 kg/mm^2) using Sandvik Cobromant Tool Holder (R and L 174.2 - 2525 M) with throw away tips having tool signature 0, 6, 11, 5, 15, 15, 1.2 by CM and PHM.

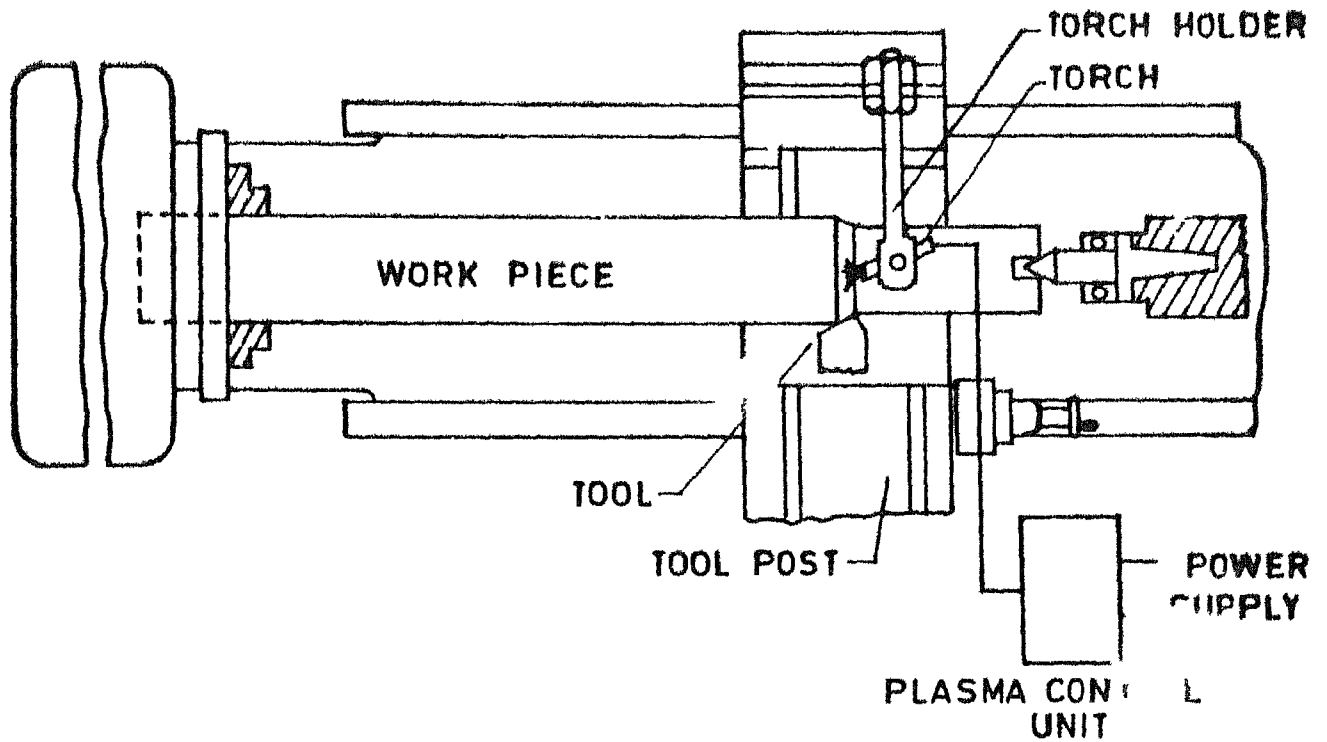


FIG 9 SCHEMATIC DIAGRAM FOR PHM

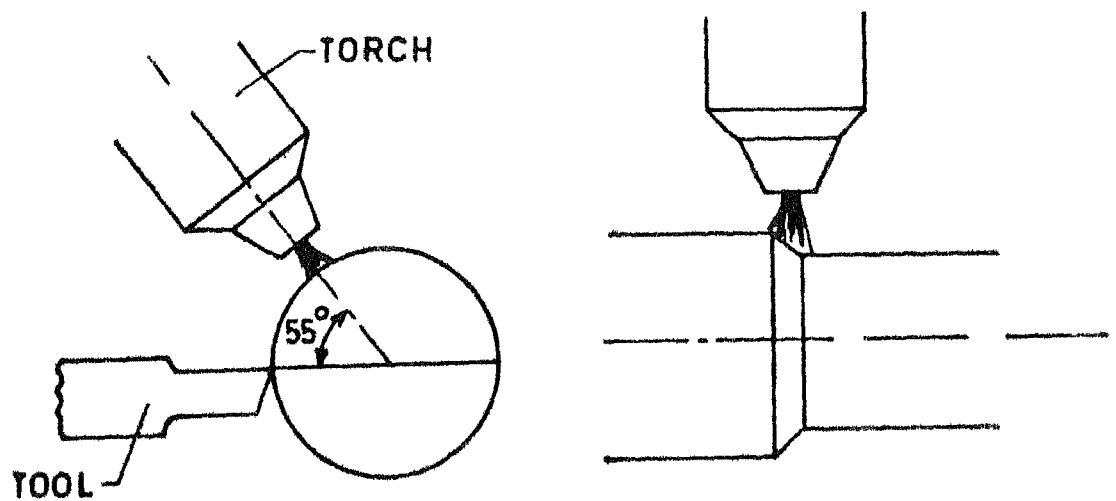


FIG 10 TORCH WORK CONFIGURATION
(After Viswananda [15])

2 3 PROCEDURE FOR MAKING SPECIMEN

Procedure for making specimen is standardized by turning it to 18 mm diameter and then using a fresh cutting edge for final depth of cut of 1 mm to avoid the effect of flank wear on residual stress. After reducing the diameter at both ends, a form tool (radius = 1.25 mm) is used to make groove A. Another form tool (angle = 68° , width = 15 mm) is used to make a groove B to ensure that elongation is along the axis.

The cutting conditions are chosen such that the machine does not vibrate. Two sets of specimens are made using the following conditions

Set-A Cutting Speed = 45 m/min, Depth of cut = 1 mm
Feed rates = 0.05, 0.10, 0.15, 0.20 and 0.25 mm/rev

Set-B Feed rate = 0.15 mm/rev, Depth of cut = 1 mm
Cutting speeds = 36, 45 and 50 m/min.

The same cutting conditions are used for making test specimens by PHM at the Argon gas pressure of 6 kg/cm^2 and flow rate of 3 lit/min. Hydrogen gas at pressure of 1 kg/cm^2 is used for shielding.

2 4 MEASUREMENT OF RESIDUAL STRESS

A schematic diagram for measuring residual stress in cylindrical specimen is shown in (Fig. 12). Etching is carried out in a glass beaker which is kept in a

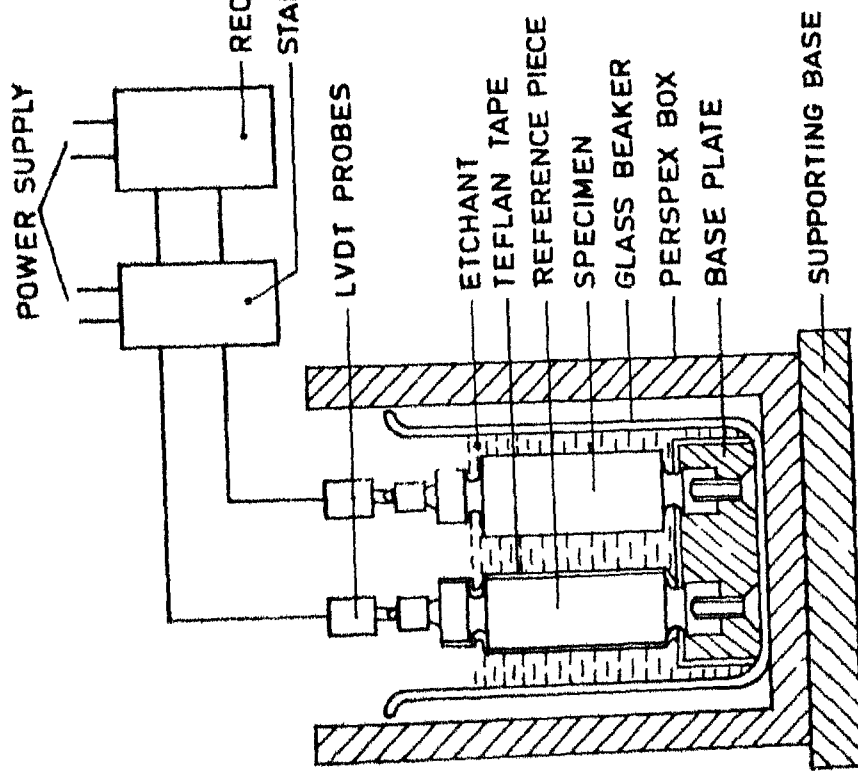


FIG 12 SCHEME FOR MEASUREMENT OF
RESIDUAL STRESS

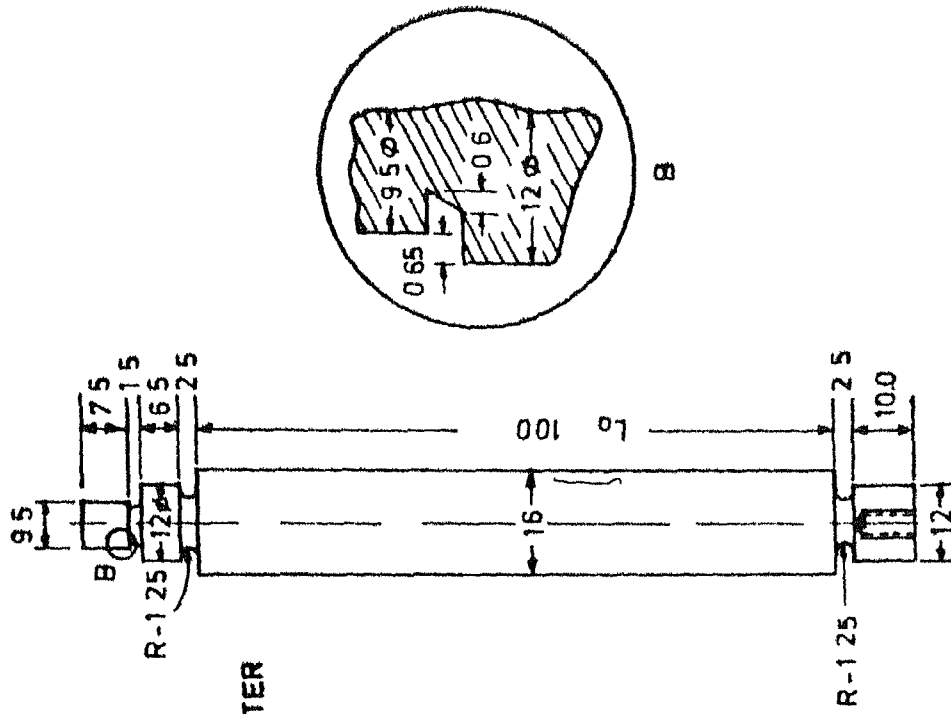


FIG 11 TEST SPECIMEN FOR
RESIDUAL STRESS
MEASUREMENT

perspex vessel. A solution of 20% nitric acid and 80% ethanol is suitable for etching [11]. The specimen is screwed to a base plate and kept in the beaker. Base plate is masked by teflon tape so that only gage length L_0 is etched. A masked reference specimen, made from En-24 steel and having same dimensions as that of the test specimen, is also screwed to the base plate for minimizing effects of temperature changes and vibrations. Tests are done during the off hours to reduce the effect of vibration resulting from working of other machines of the laboratory.

2 4 1 Determination of Chemical Machining Rate

Ten pieces of 16 mm diameter and 20 mm length are made from En-24 steel and weighed individually. All surfaces except one circular surface are masked by teflon tape. All pieces are kept in etching solution (20% nitric acid, 80% ethanol) at the same time. Test pieces are taken out from the vessel after lapse of 1, 2, 3, 4, 6, 8, 10, 12, 16 and 20 minute. Test pieces are weighed again. The chemical machining rate K is calculated from the loss in weight and density of En-24 steel. Average chemical machining rate $K = 3 \times 10^{-3}$ mm/min as determined is used in the calculation.

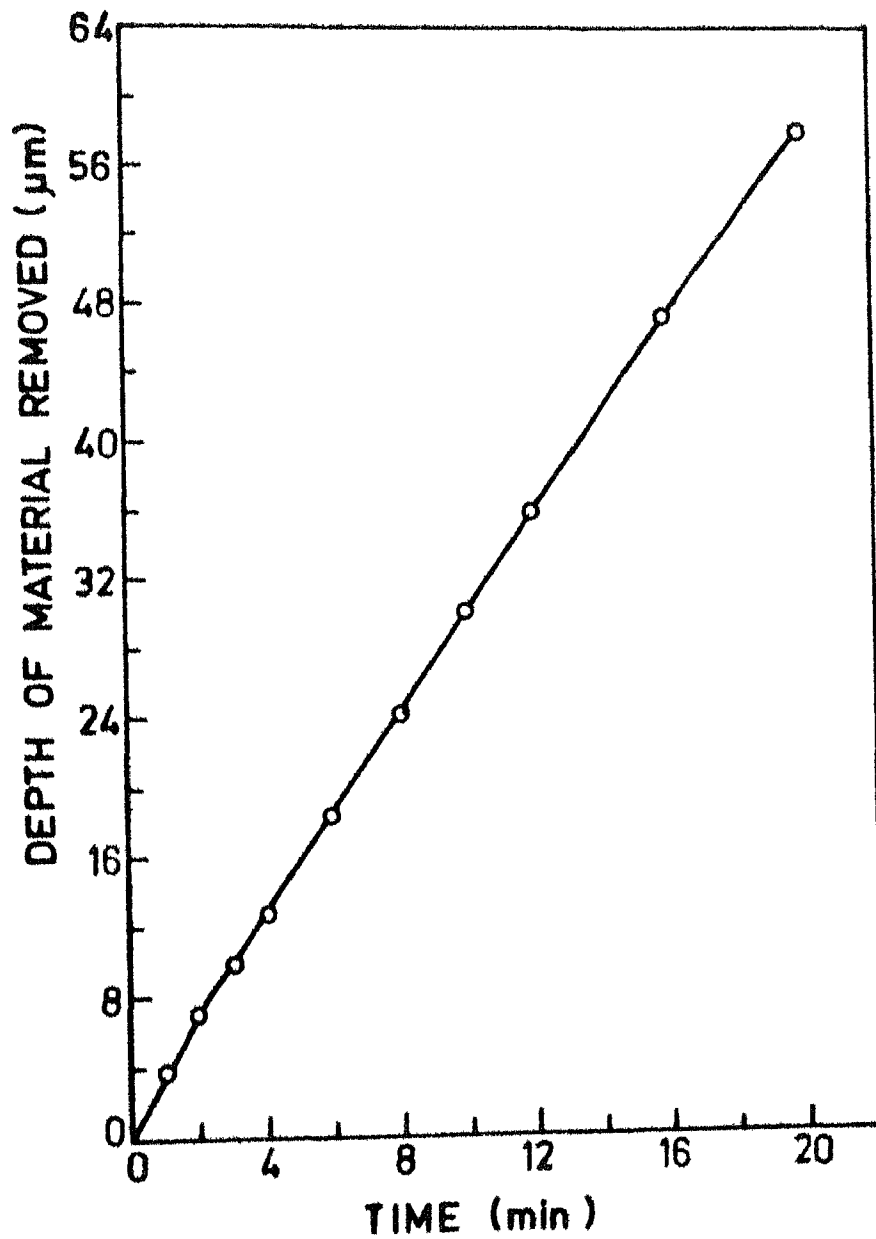


FIG 12-a VARIATION OF DEPTH OF MATERIAL REMOVED WITH TIME

2 4.2 Experimental Set-up and Procedure

Change in length of the specimen is measured with a linear variable differential transformer (LVDT) [Starrett Lever Type Gaging Head) Two measuring heads are used, one placed on the test specimen and the other on the reference piece. LVDTs are connected to Taut Band-Meter (Starrett Electronic Gage, Least Count = 0.00025 mm) The output of the meter provides differential signal which is recorded on a Omni Scribe Recorder

CHAPTER-3

RESULTS AND DISCUSSION

3.1 GENERAL

The results of experiments conducted by Conventional Machining (CM) and Plasma Hot Machining (PHM) are presented in this chapter. The effects of cutting speed and feed rate on residual stress are discussed. A comparison between CM and PHM is made.

3.2 EXPERIMENTAL RESULTS

The records of change in length vs distance are shown in Fig. 13 for various feed rates and in Fig. 14 for various speeds during CM and PHM.

3.3 CALCULATION OF RESIDUAL STRESS

Values of elongation (1) and rate of change of elongation (dl/dt) are read from Figs. 13 and 14 and residual stress is calculated with the help of equation (2) using the experimental value of etching rate K .

3.4 EFFECT OF FEED RATE ON RESIDUAL STRESS

Fig. 15 shows the behaviour of residual stress at various feed rates from 0.05 to 0.25 mm/rev for CM.

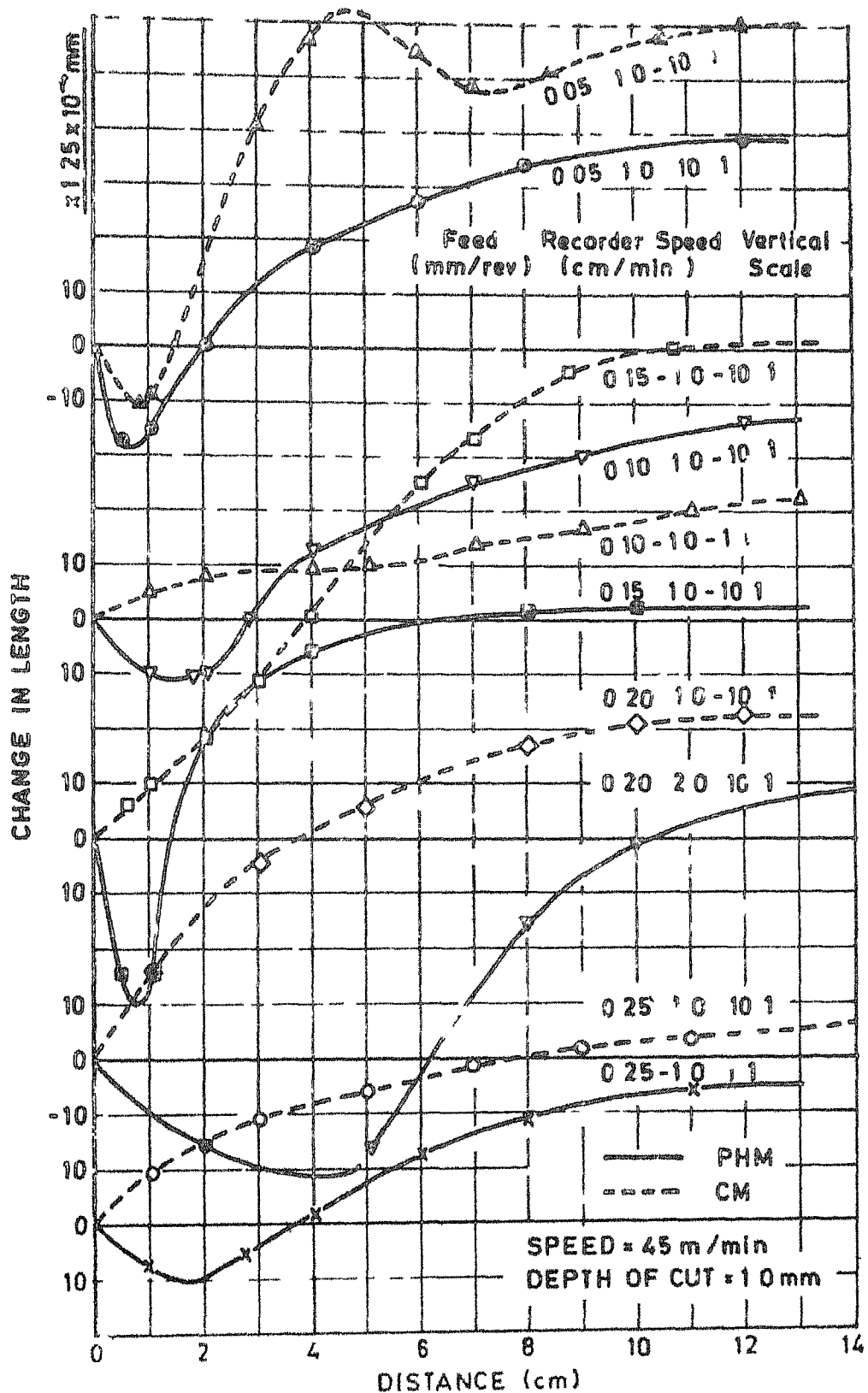


FIG 13 CHANGE IN LENGTH VS DISTANCE AT DIFFERENT FEED RATES DURING CM AND PHM

N.B. Feed, Recorder-speed and Vertical Scale are Indicated on the Graphs Respectively.

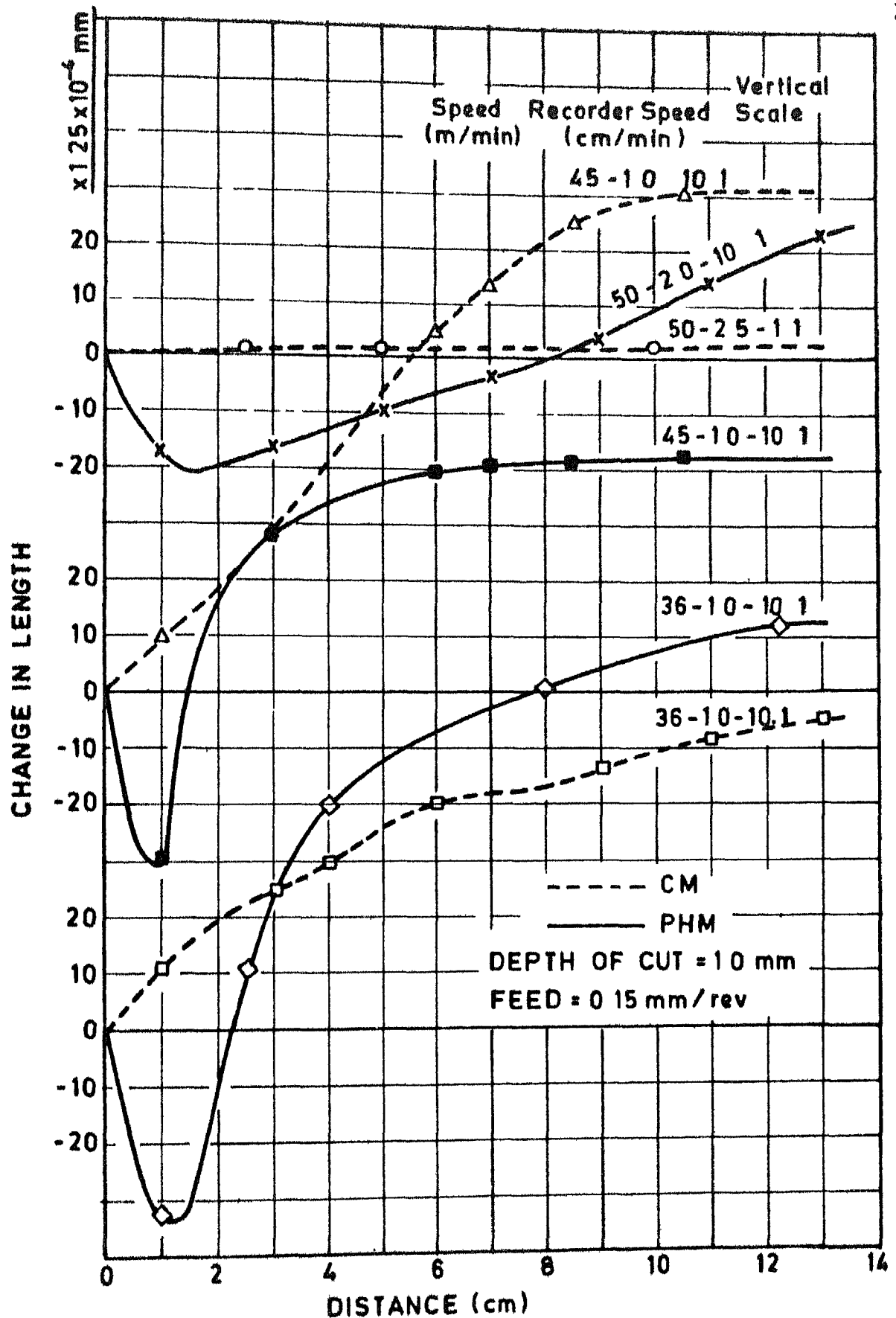


FIG 14 CHANGE IN LENGTH VS DISTANCE AT VARIOUS SPEEDS DURING CM AND PHM

N.B. Speed, Recorder-speed and Vertical Scale are Indicated

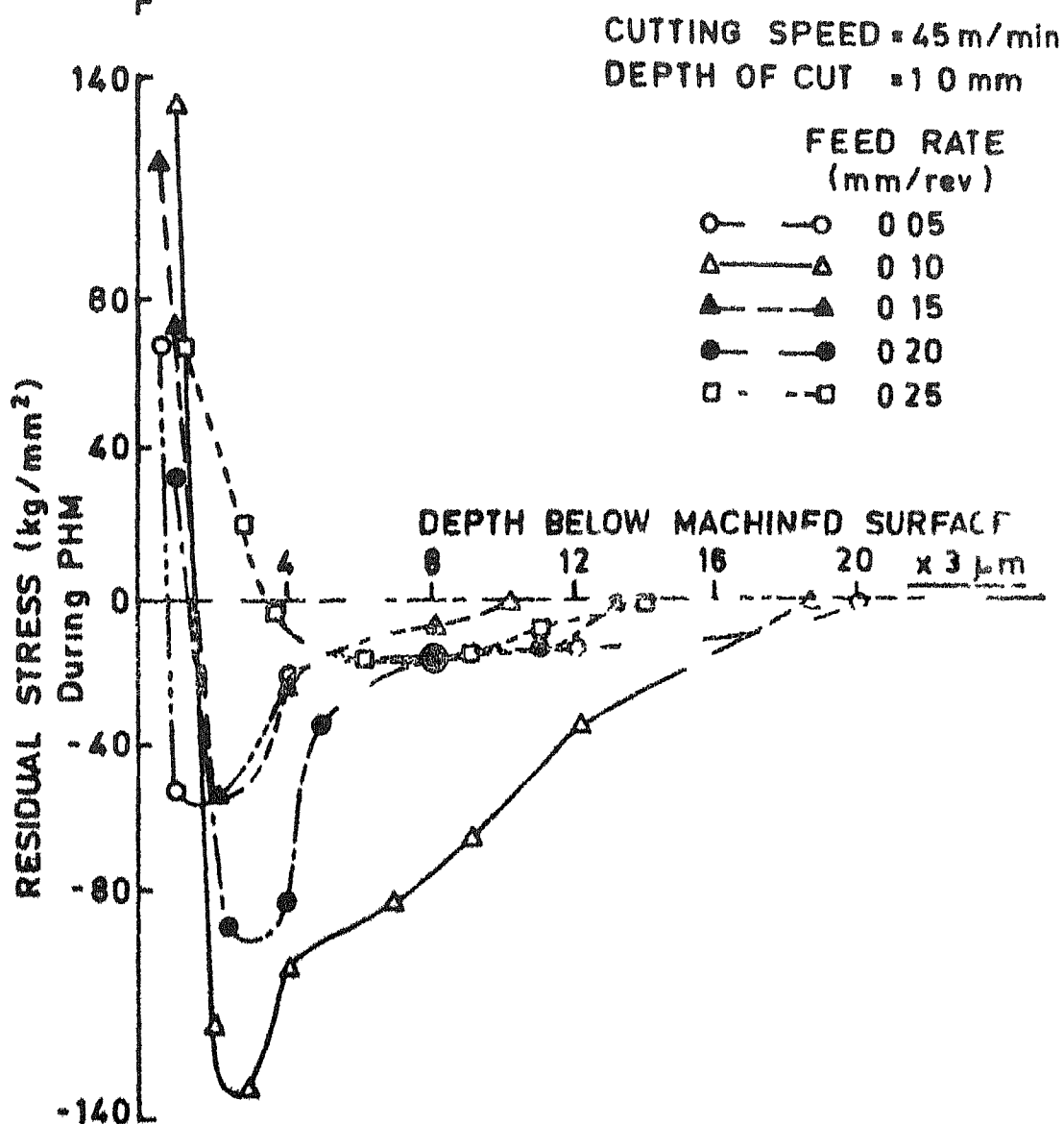
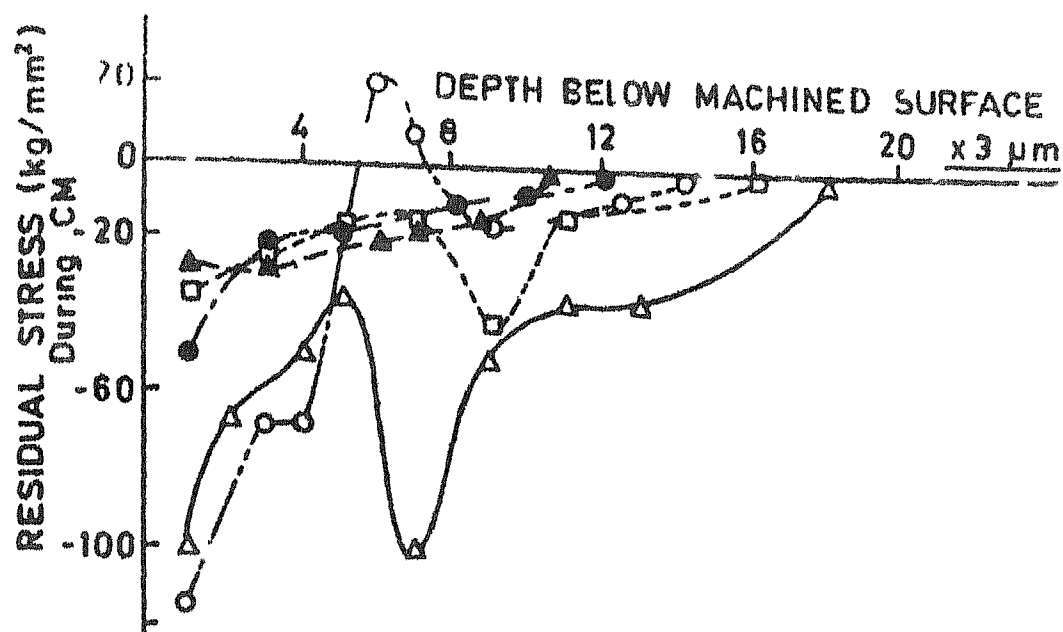


FIG 15 RESIDUAL STRESS VS DEPTH BELOW MACHINED SURFACE AT VARIOUS FEED RATES

and PHM Fig 18 shows the variation of maximum compressive residual stress with feed rate and speed.

It is observed that residual stress in CM in general, is compressive as also observed by Israeli and Papiar [11]* and near the surface maximum residual stress decreases with increase in feed rate (Fig 18-a)

For the case of PHM, it is observed that residual stress near the surface of the workpiece is tensile and it becomes compressive at depths varying from 2.4 to 7.5 μm

Fig 16 shows maximum depth of stressed layer vs. feed rate for CM and PHM It is seen that the depth of the stressed layer is nearly same in both cases However, minimum depth of stressed layer occurs at 0.15 mm/rev feed in CM and PHM

3.5 EFFECT OF CUTTING SPEED ON RESIDUAL STRESS

Fig 17 shows the behaviour of residual stress at cutting speeds of 36, 45 and 50 m/min for CM and PHM

It is observed that residual stress is always compressive in CM Furthermore, the residual stress is not affected by cutting speed in the small range in which

* The stresses shown in Fig 7 and 8 of reference [11] are compressive and not tensile as confirmed through private communication with author.

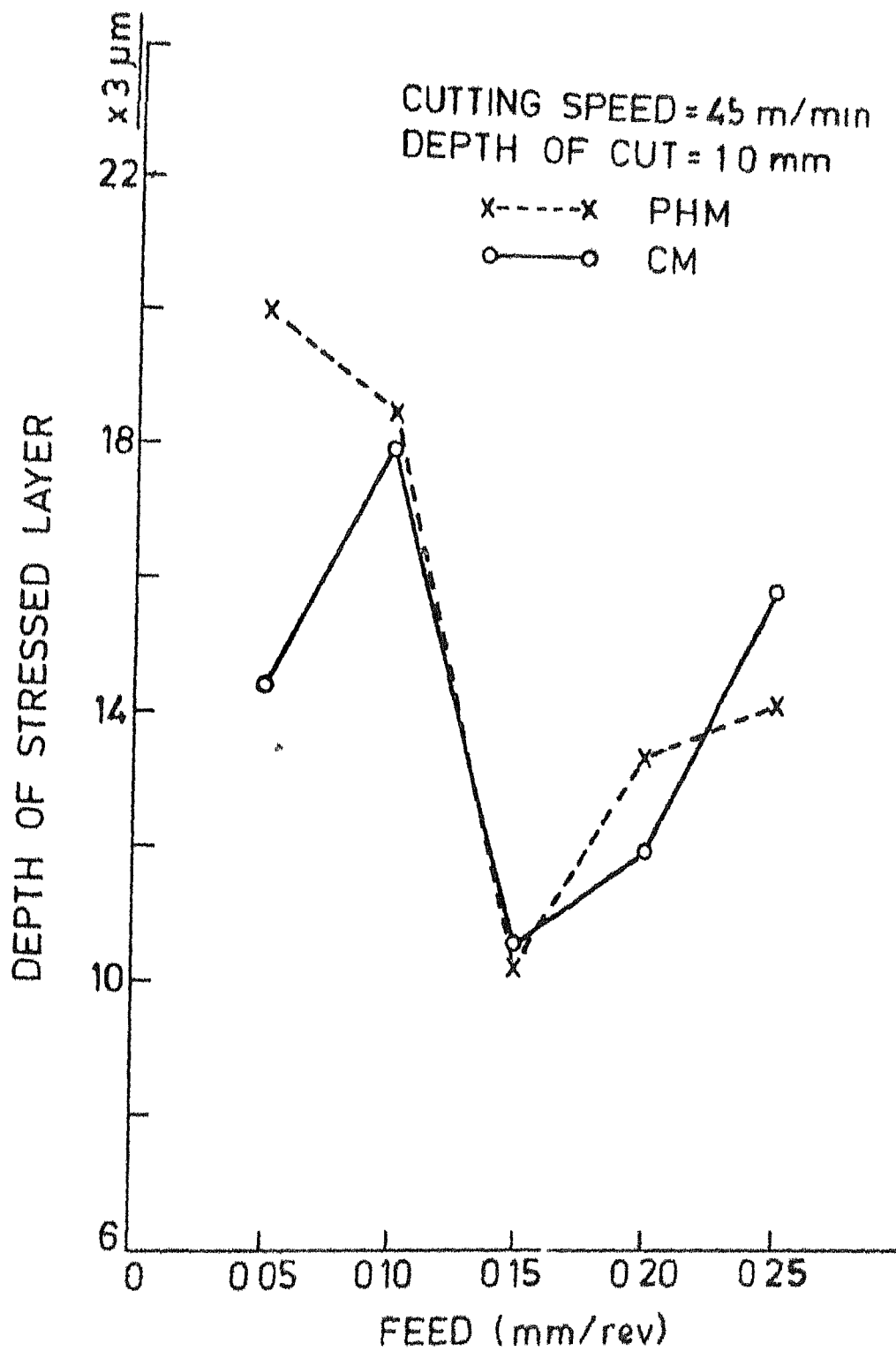


FIG 16 DEPTH OF STRESSED LAYER VS FEED
IN CM AND PHM

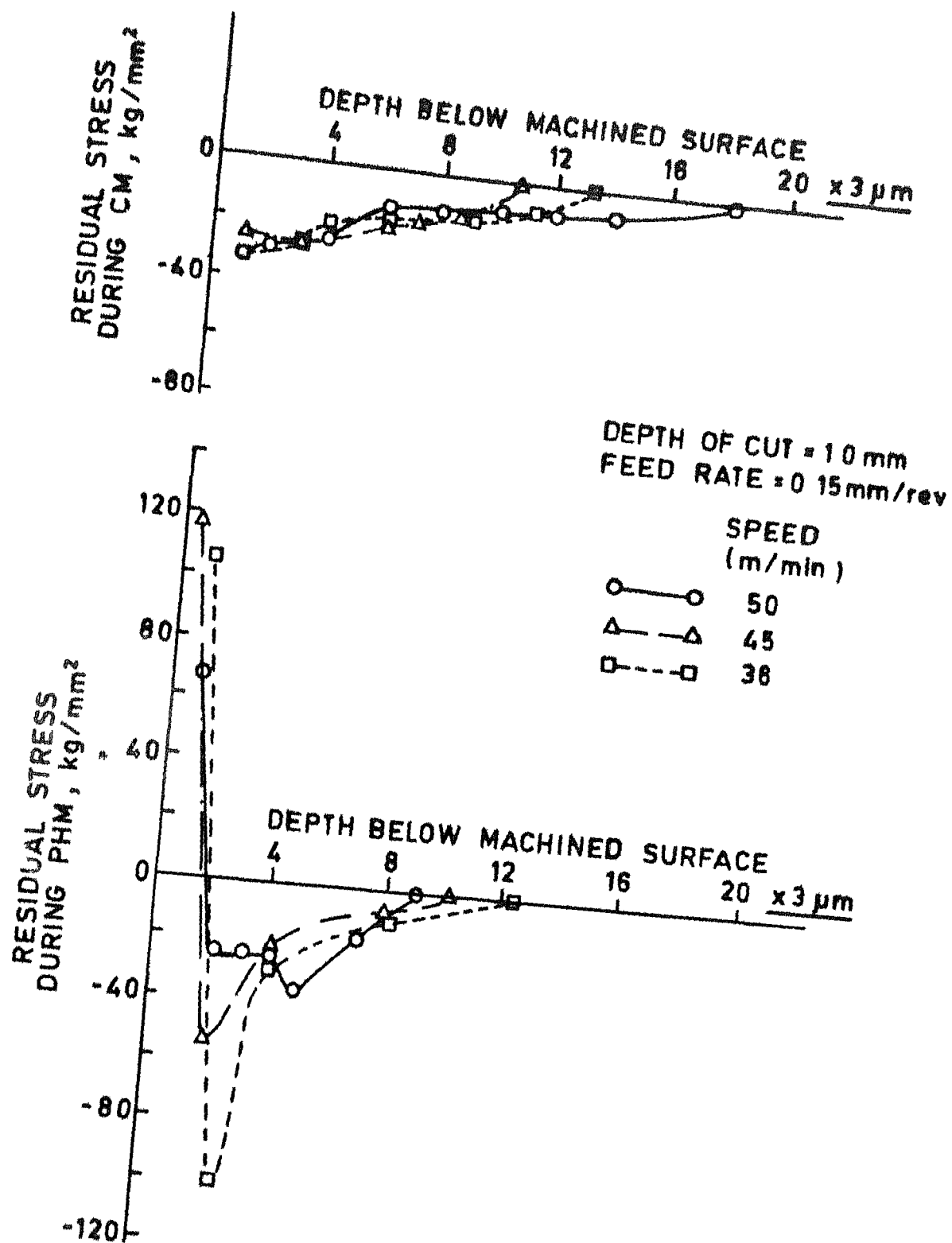


FIG 17 RESIDUAL STRESS VS DEPTH BELOW MACHINED SURFACE AT VARIOUS SPEEDS

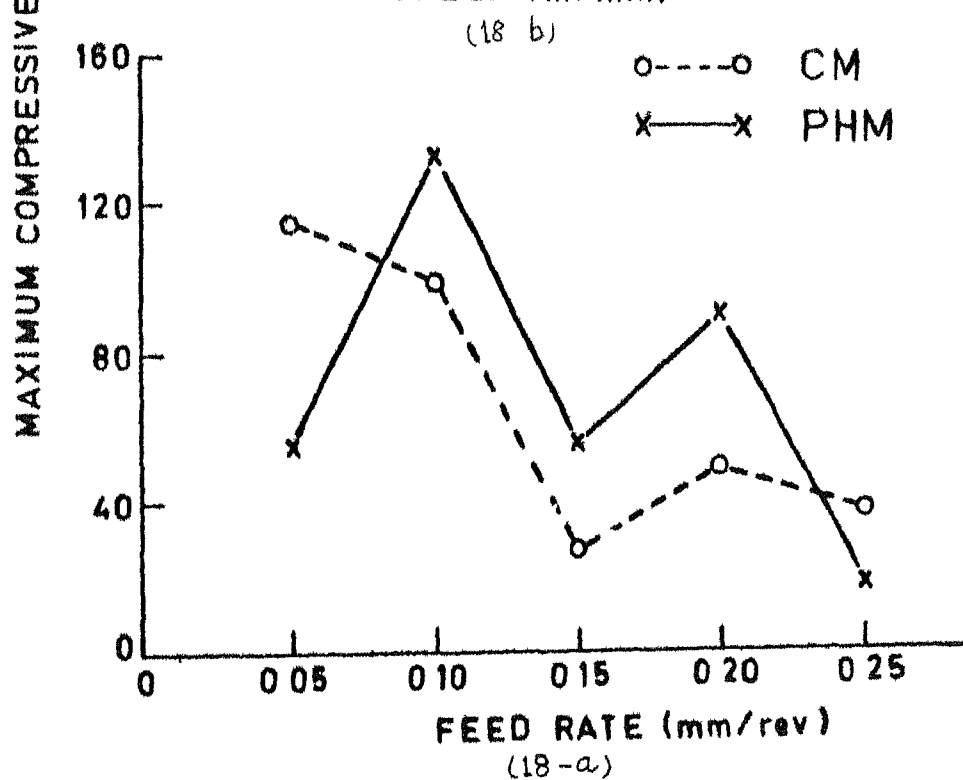
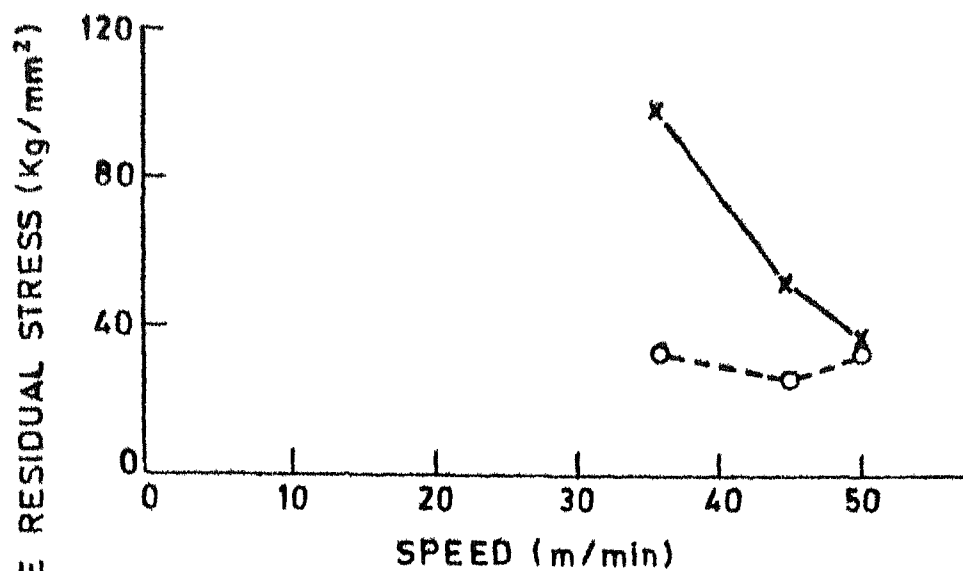


FIG 18 MAXIMUM COMPRESSIVE RESIDUAL STRESS VS SPEED AND FEED RATE IN CM AND PHM

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tests are carried out

It is observed that residual stress is tensile near the surface with PHM. Residual stress changes to compressive at depths varying from 3.6 to 5.5 μm . As cutting speed increases maximum compressive residual stress decreases. (Fig. 18-b)

Experimental results of Vishwananda [15] are used to make an approximate estimate of rise in temperature in PHM. For the cutting conditions used, the temperature ^{rise} in PHM is approximately 60°C as compared to CM. Residual stress near the surface is tensile with PHM due to increase in temperature of work-material.

3.6 ACCURACY OF MEASUREMENT OF RESIDUAL STRESS

Measurement of residual stress depends upon the accuracy of measuring slope (dl/dt) of elongation versus time curve. It is found that slope depends upon accuracy of LVDT probes, electronic meter and finally recorder. There is a limitation in the sensitivity used as the recorder becomes unstable at higher sensitivity. In the present experiment, slope could be measured within an accuracy of $\pm 10\%$. Therefore calculated value of residual stresses are accurate within $\pm 10\%$.

3 7 THREE DIMENSIONAL NATURE OF RESIDUAL STRESS

Residual stresses are caused due to cutting forces in turning operation. Thus residual stresses would exist in feed, tangential and radial directions. Results of Doi and Uka1 [10] show that the residual stress in radial direction (Fig 4 of Ref [10]) is negligible as compared to the stresses in other two directions. The theoretical analysis of Baur and Heyn assumes residual stress in axial direction (feed direction) only. However, in the specimen, the stress in tangential direction may also be of the same order. Thus the experimental results are affected by residual stress in the tangential direction.

Considering negligible stress in radial direction, strain in axial direction is given by

$$e_x = (S_x - \nu S_y)/E \quad (3)$$

$$= (S_x - \nu C S_x)/E = S_x(1 - \nu C)/E$$

$$S_x = E e_x / (1 - \nu C) \quad (4)$$

where e_x is strain in axial direction, S_x and S_y are stresses in feed and tangential directions respectively. E is Young's modulus, ν is Poisson ratio and $C = S_y/S_x$.

The residual stress measured in the present experiment is related to the term $E e_x$. Thus a correction factor $1/(1 - \nu C)$ should be used to account for the

residual stress in the tangential direction. The variation of the correction factor with C (ratio of residual stress in tangential and feed direction) is shown in

Fig. 19. The results of Doi and Ukai [10] show that the value of $C \approx 1$. Thus an approximate estimate would show that the residual stress calculated from equation (2) need to be modified by a factor of 1.5 to take into account the effect of residual stress in the tangential direction.

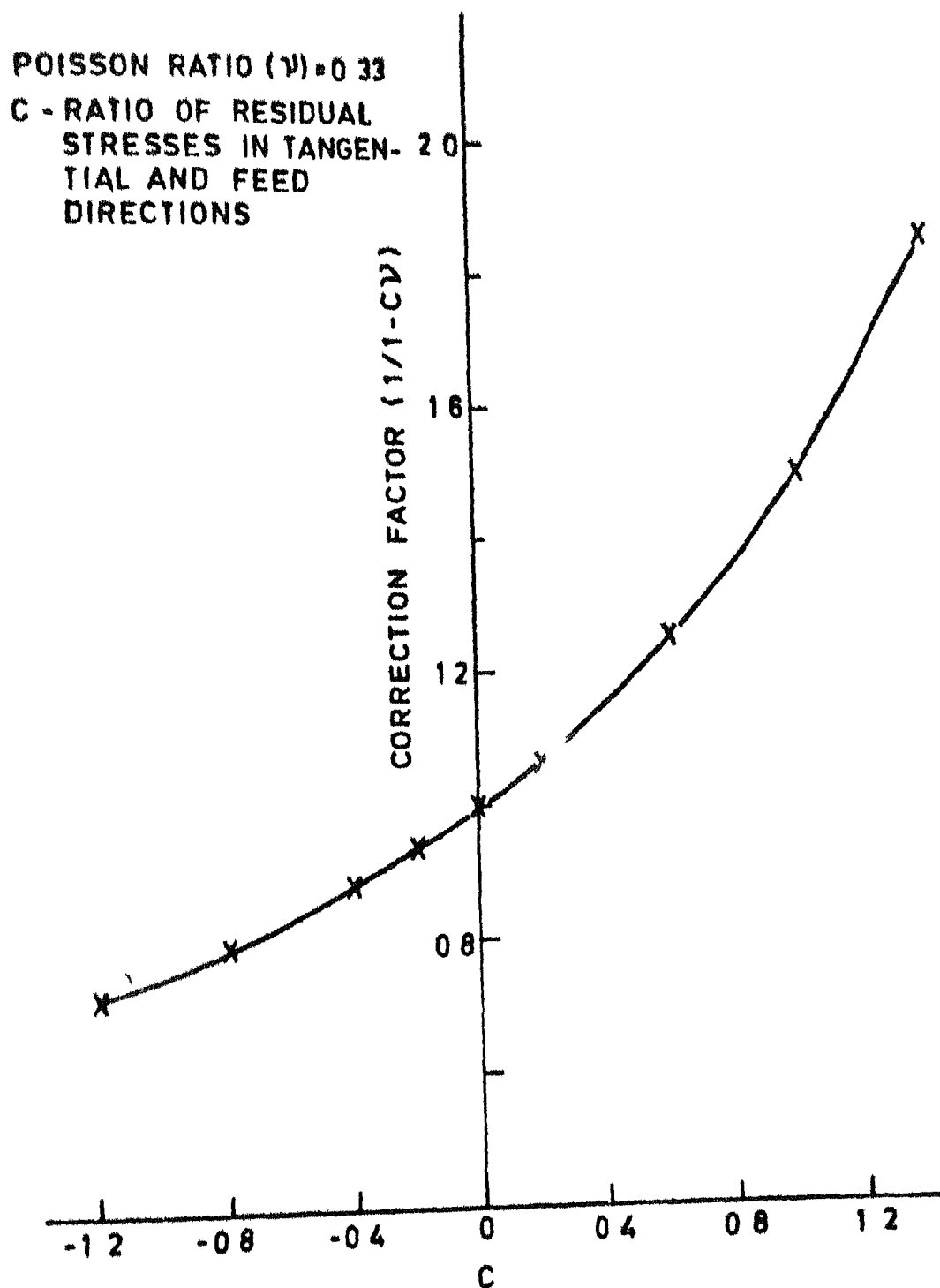


FIG 19 CORRECTION FACTOR VS RESIDUAL STRESS RATIO

CHAPTER-4

CONCLUSIONS AND SCOPE FOR FUTURE WORK

4.1 CONCLUSIONS

The following conclusions are drawn from the results of residual stress during Conventional Machining (CM) and Plasma Hot Machining (PHM)

- (1) Residual stress is compressive during CM.
- (2) Residual stress is tensile near the surface during PHM
- (3) Depth of stressed layer is nearly same at all feed rates.
- (4) Minimum depth of stressed layer occurs at 0.15 mm/rev/in ^{feed} in CM and PHM

4.2 SCOPE FOR FUTURE WORK

The analysis used is suitable for residual stress in axial direction. As in actual practise, residual stress exist in other two directions also, there is a need to develop comprehensive theoretical analysis which would take care of residual stresses in three directions

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